

Charged Particle Fluctuations as a Signal of the Dynamics of Heavy Ion Processes

Fritz W. Bopp and Johannes Ranft

Universität Siegen, Fachbereich Physik,
D-57068 Siegen, Germany

February 1, 2008

Abstract

Comparing proposed quantities to analyze charged particle fluctuations in heavy ion experiments we find the dispersion of the charges in a central rapidity box as best suited. Various energies and different nuclear sizes were considered in an explicit Dual-Parton-Model calculation using the DPMJET code. A definite deviation from predictions of recently considered statistical models was obtained. Hence the charged particle fluctuations should provide a clear signal of the dynamics of heavy ion processes. They should allow to directly measure the degree of thermalization in a quantitative way.

1 Introduction

In the analysis of the hadronic multi-particle production (for a recent review see [1]) a key observation has been the local compensation of charge[2]. The charge fluctuations connected to the soft hadronic part of the reactions were found to involve only a restricted rapidity range. This observation limited the applicability of statistical models to rather local fluctuations (see e.g. [3] where the charge fluctuation between the forward and backward hemisphere[4] was discussed).

In heavy ion scattering charge flow measurements should be analogously decisive. It is a central question of an unbiased analysis whether the charges are distributed just randomly or whether there is some of the dynamics left influencing the flow of quantum numbers. This is not an impractical conjecture. In heavy ion experiments the charge distribution of particle contained in a central box with a given rapidity range $[-Y_{\max.}, +Y_{\max.}]$ can be measured and the dispersion of this distribution:

$$\langle \delta Q^2 \rangle = \langle (Q - \langle Q \rangle)^2 \rangle \quad (1)$$

can be obtained to sufficient accuracy. For sufficiently large gaps this quantity also reflects the long range charge flow.

It was proposed to use this quantity to distinguish between particles emerging from a equilibrated quark-gluon gas or from a equilibrated hadron gas[5, 6, 7]. In a hadron gas each particle species in the box is taken essentially poissonian. In a central region where the average charge flow can be ignored, one obtains a simple relation for particles like pions with charges 0 and ± 1 :

$$\langle \delta Q^2 \rangle = \langle N_{\text{charged}} \rangle . \quad (2)$$

It is argued in the cited papers that this relation would change in a quark gluon gas to:

$$\langle \delta Q^2 \rangle = \sum_i q_i^2 \langle N_i \rangle = 0.19 \langle N_{\text{charged}} \rangle \quad (3)$$

where q_i are the charges of the various quark species and where again a central region is considered. The coefficient on the right was calculated[6] for a two flavor plasma in a thermodynamical consideration which predicts various quark and gluon contributions with suitable assumptions. A largely empirical final charged multiplicity $N_{\text{charged}} = \frac{2}{3}(N_{\text{glue}} + 1.2N_{\text{quark}} + 1.2N_{\text{antiquark}})$ was used.

It should be pointed out that the estimate is not trivial. In the considered $m_{\text{quark}} = 0$ theory the observable Q is not infrared safe and makes no sense. A way to make it well defined[8] is to consider the quantity:

$$Q_{\text{quark}} \rightarrow \tilde{Q}_{\text{quark}} = Q_{\text{quark}} - \langle Q_{\text{quark}} \rangle \quad (4)$$

which avoids the influence of extra sea quarks. Such a correction is also needed to have an observable which can be expected to survive hadronization. Numerically the effect is not very big and the problems can be ignored if only a rough description is sufficient.

There are a number of sources of systematic errors in the above comparison. The result strongly depends on what one chooses as primordial and secondary particles. Considering these uncertainties we follow Fiałkowski's conclusion[9] that a clear cut distinction between the hadron- and the quark gluon gas is rather unlikely. This does not eliminate the interest in the dispersion. The hadron gas model is anyhow no optimal reference point to compare with.

In the next section we discuss various possible measures to observe such fluctuations. We favor the dispersion of the charge transfer. Using an explicit Dual Parton model calculation we observe a clear distinction between models with local compensation of charge and equilibrium approaches. In section 3 a simple interpretation of the dispersion in terms of quark lines is outlined. This suggests to compare the dispersion to the particle density as it is done in section 4.

2 Various Measures for Fluctuations in the Charge Distribution

For the analysis of the charge structure several quantities were discussed in the recent literature. It was proposed to look at the particles within a suitable kinematic region and to measure just the mean standard deviation of the ratio R of positive to negative particles:

$$\langle \delta R^2 \rangle = \left\langle \left(\frac{N_+}{N_-} - \left\langle \frac{N_+}{N_-} \right\rangle \right)^2 \right\rangle \quad (5)$$

or the quantity F :

$$\langle \delta F^2 \rangle = \left\langle \left(\frac{Q}{N_{\text{charged}}} - \left\langle \frac{Q}{N_{\text{charged}}} \right\rangle \right)^2 \right\rangle \quad (6)$$

where $Q = N_+ - N_-$.

We consider them not attractive. The quantities are not suitable for small intervals, as there are actually undefined in a certain region. They are less clean than the dispersion, $\langle \delta Q \rangle$, as they are not exclusively connected to the flavor structure and as they mix up charge and density fluctuations.

For large nuclei at high energies this is not a problem as the density fluctuations are small and all three quantities are connected by the following relations[6]:

$$\langle N_{\text{charged}} \rangle \langle \delta R^2 \rangle = 4 \langle N_{\text{charged}} \rangle \langle \delta F^2 \rangle = 4 \cdot \frac{\langle \delta Q^2 \rangle}{\langle N_{\text{charged}} \rangle}. \quad (7)$$

To examine the range where these relations hold, all three quantities were calculated in the Dual Parton model implementation DPMJET[15]. For the most central 5% Pb-Pb scattering at LHC energies ($\sqrt{s} = 6000$ A GeV) there is indeed a perfect agreement between all three quantities as shown in figure 1. For the most central 5% S-S scattering at RHIC energies ($\sqrt{s} = 200$ A GeV) the agreement is no longer as good. For the minimum bias S-S scattering at RHIC energies the

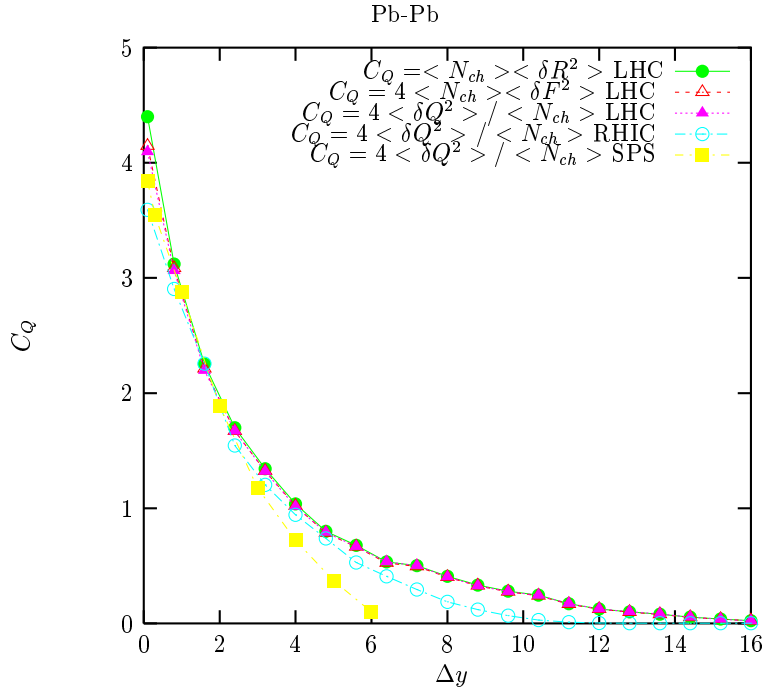


Figure 1: Charge fluctuations for the most central 5% Pb-Pb scattering at LHC energies ($\sqrt{s} = 6000$ A GeV). Also shown are dispersions for RHIC ($\sqrt{s} = 200$ A GeV) and SPS (E_{ab} A GeV) energies.

agreement is lost and the first two expressions behave rather erratic. The same erratic behavior is seen for the proton-proton case which is shown figure 2. As any conclusion will strongly depend on a comparison of central processes with minimum bias events, we advocate to stick to the dispersion of the net charge distribution $\langle \delta Q^2 \rangle$.

We observed no significant difference between rapidity and pseudo-rapidity boxes.

3 A Simple Relation between the Quark Line Structure and Fluctuations in the Charge Flow

To visualize the meaning of charge flow measurements it is helpful to introduce a general factorization hypothesis. It is not exact but it is widely expected to hold to good accuracy. It postulates that the flavor structure of an arbitrary amplitude can be described simply by an overall factor, in which the contribution from individual quark lines factorize¹.

The hypothesis can be used to obtain the following generalization of the Quigg-Thomas relation[12, 13, 14]. This generalization states that the correlation of the charges $Q(y_1)$ and $Q(y_2)$, which are

¹ The hypothesis is based on the exchange degeneracy of octet and singlet Regge trajectories effectively changing the $SU(N_{\text{effective}})$ flavor symmetry to an $U(N_{\text{effective}})$ symmetry in which this relation is exactly valid. One of the important corrections to the hypothesis originates in the special behaviour of the masses of the lowest lying mesons of the trajectories, which is especially significant in the pseudo-scalar sector between the π_0 and the η meson. That one of the two neutral states is sometimes suppressed, introduces a mild anticorrelation between neighbouring flavors, which can be ignored for our consideration centered at long range charge transfers.

If a higher accuracy is desired the hypothesis can be restricted to primordial particles generated at a high “temperature” and “secondary” charges produced during the decay of primordial particles can be considered extra. With simple assumptions their contribution can be related to the corresponding particle spectrum. If all charged particles were secondaries the dispersion of the charge transfer across an arbitrary rapidity boundary would be given by the Quigg-Thomas relation[10, 11, 12] $\langle \delta Q^2(y) \rangle = \sigma \frac{1}{2} \rho_{\text{charged}}(y)$ where $\sigma = 1$ if widening and narrowing effects balance.

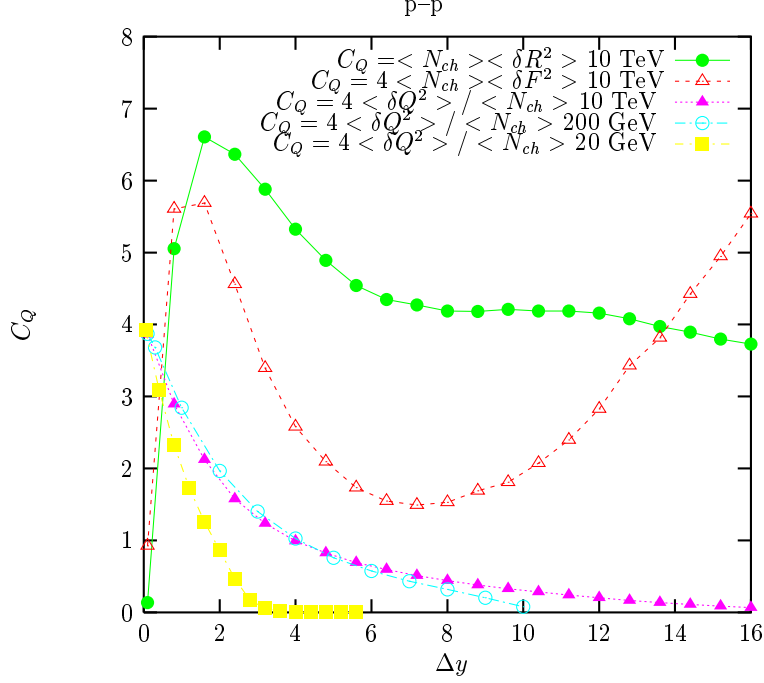


Figure 2: Charge fluctuations for minimum bias pp scattering at SPS, RHIC and LHC energies

exchanged during the scattering process across two separate kinematic boundaries, is just:

$$\langle \{Q(y_1) - \langle Q(y_1) \rangle\} \{Q(y_2) - \langle Q(y_2) \rangle\} \rangle = n_{\text{common lines}} \langle (q - \langle q \rangle)^2 \rangle. \quad (8)$$

where $n_{\text{common lines}}$ counts the number of quark lines intersecting both borders and q is the charge of the quark on such a line. Depending on the flavor distribution average values $\langle (q - \langle q \rangle)^2 \rangle = 0.22 \dots 0.25$ are obtained.

Most observables of charge fluctuations depend on this basic correlation. The fluctuation of the charges within a $[-Y_{\text{max.}}, +Y_{\text{max.}}]$ box discussed above contains a combination of three such correlations:

$$\langle \delta Q^2 \rangle = \langle \delta Q(y_1)^2 \rangle + \langle \delta Q(y_2)^2 \rangle - 2 \langle \delta Q(y_1) \cdot \delta Q(y_2) \rangle. \quad (9)$$

Using (8) the dispersion of the charges in a box subtracts to:

$$\langle \delta Q[\text{box}]^2 \rangle = n_{\text{lines entering box}} \langle (q - \langle q \rangle)^2 \rangle \quad (10)$$

where $n_{\text{lines entering box}}$ is the number of quark lines entering the box.

4 Calculation of the Dispersion of the Charge Distribution within a Box

Let us consider the prediction of a thermodynamic model in more detail. In the thermodynamic limit with an infinite reservoir outside and a finite number of quarks inside all quark lines will connect to the outside as shown in figure 3. The dispersion of the charge transfer is therefore proportional to the total number of particles inside. In the hadron gas all particles contain two independent quarks each contributing with roughly 1/4 yielding the estimate of (2). For the quark gas only one quark originates in the thermalization and is taken to be responsible for charge

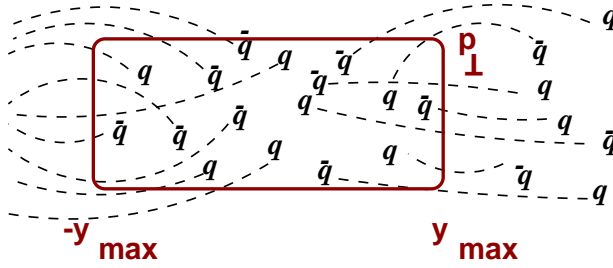


Figure 3: Quark lines entering the box in the thermodynamic limit

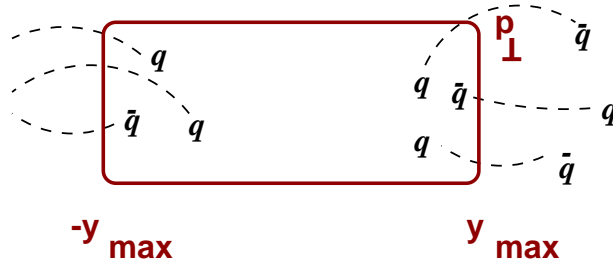


Figure 4: Quark lines entering the box with local compensation of charge

transfer yielding a considerable smaller result. Obviously there are several refinements to this simple picture.

Let us consider the limit of a tiny box. Looking only at the first order one trivially obtains:

$$\langle \delta Q^2 \rangle / \langle N_{\text{charged}} \rangle = 1 \quad (11)$$

which corresponds to the hadron gas value.

If the box size increases to one or two units of rapidity on each side this ratio will typically decrease, as most models contain a short range component in the charge fluctuations usually attributed to secondary interactions. One particular short range fluctuation might be caused by the hadronization of partons of the quark gluon gas. The quark antiquark pair needed for the hadronization is assumed to be short range so that for a box of a certain size one just obtains the charge dispersion of the original partons. This is responsible for the reduction of the fluctuation discussed above. The decreasing is however not very distinctive. Common to many models are secondary interactions which involve decay processes and comover interaction. In hadron hadron scattering processes such correlations are known to play a significant role and there is no reason not to expect the same for the heavy ion case.

After a box size passed the short range the decisive region starts. In all global statistical models[5, 7, 6] the ratio will have to reach now a flat value. Only for very large rapidity ranges charge conservation will force the ratio to drop ($\propto 1 - y_{\text{max.}}/Y_{\text{kin.max.}}$). This is different in string models as it is illustrated in figures 1 and 2. The model calculation shows with its rapid fall off a manifestly different behavior. It is a direct consequence of the local compensation of charge contained in string models. The effect is illustrated in Figure 4 in which only quark lines which contribute to the charge flow and which intersect the boundary are shown. The local compensation of charge allows now only a contribution of lines originating around the boundaries. If the distance is larger than the range of charge compensation the dispersion will no longer increase with the box size. The total contribution will now be just proportional to the density of the particles around the boundaries

$$\langle \delta Q^2 \rangle \propto \rho_{\text{charged}}(y_{\text{max.}}). \quad (12)$$

This resulting scaling is illustrated in a comparison between both quantities shown in Figure 5 for RHIC and LHC energies. The agreement is comparable to the proton proton case shown

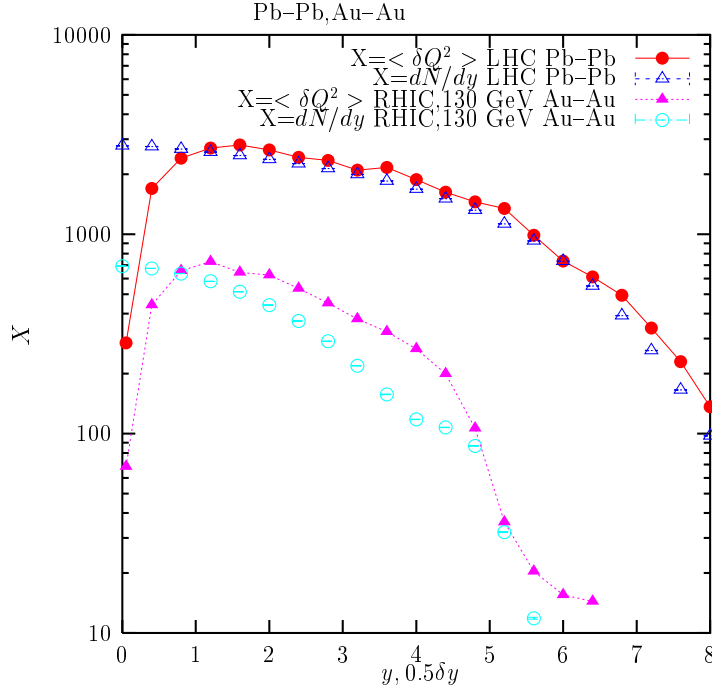


Figure 5: Comparison of the dispersion of the charge distribution with the density on the boundary of the considered box for central gold gold resp. lead lead scattering at RHIC and LHC energies.

in Figure 6. The proportionality is expected to hold for a gap with roughly $\frac{1}{2}\delta y > 1$. For smaller boxes some of the quark lines seen in the density do not contribute as they intersect both boundaries. For large rapidity sizes there is a minor increase from the leading charge flow Q_L originating in the incoming particles. In a more careful consideration[14] one can subtract this contribution

$$\langle \delta Q^2 \rangle_{\text{leading charge migration}} = \langle Q_L \rangle (1 - \langle Q_L \rangle) \quad (13)$$

and concentrate truly on the fluctuation.

The prediction for the proportionality factor for the case of mere short range fluctuations would be roughly a factor one (see footnote 1). In string models primordial particles are responsible for a longer range charge transfer coming from the contributions of the quark resp. diquark fragmentation chains. Taking everything together one obtains

$$\langle \delta Q^2 \rangle = \sum_{\text{left+right}} \{ n_{\text{strings}} \cdot \langle (q - \langle q \rangle)^2 \rangle + f_{\text{secondary}} \sigma \frac{1}{2} \rho_{\text{charged}}(y) \} \quad (14)$$

where n_{strings} is the number of strings where $f_{\text{secondary}}$ is the fraction of secondary to primary particles and where the width of the local fluctuations σ is roughly unity. In our Dual Parton Model calculation we observe factor of roughly 1.2 between the density and the dispersion. It means that most of the fluctuation originate in secondary interaction and that the effective larger coefficient of the first term which significantly rises the factor plays only a lesser role.

Conclusion

In the paper we demonstrated that the dispersion of the charge distribution in a central box of varying extend in rapidity is an extremely powerful measure. Within the string model calculation the dispersion seen in relation to the spectra shows no difference between simple proton proton

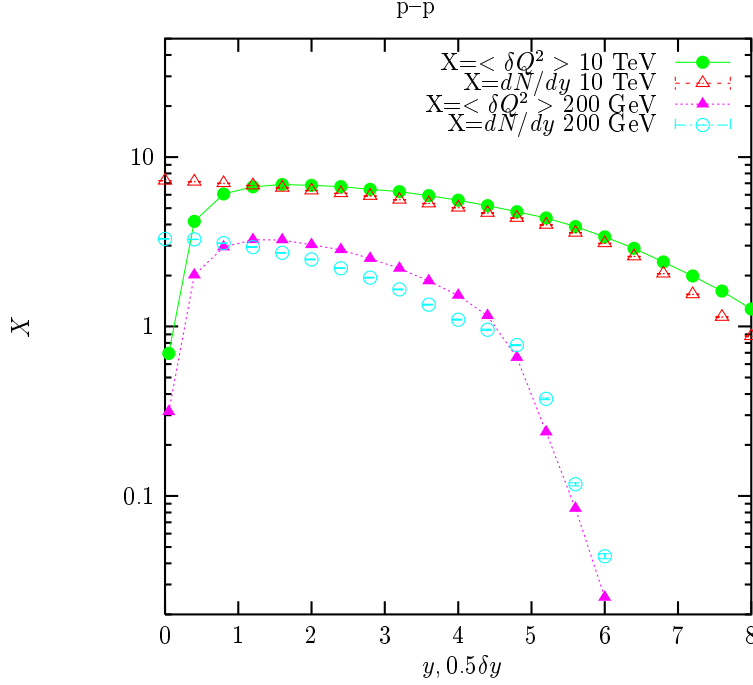


Figure 6: Comparison of the dispersion of the charge distribution with the density on the boundary of the considered box for proton proton scattering at RHIC and LHC energies.

scattering and central lead lead scattering even though both quantities change roughly by a factor of 400.

The dispersion allows to clearly distinguish between conventional string models and thermal models. As most expected changes in the dynamic are somehow connected to the onset of thermalization they will introduce more fluctuations. Even if the truth should lie somewhere in between string models and quark gluon plasma models it is therefore quite reasonable to hope that the position of the transition can be determined in a quantitative way.

Acknowledgments

F.W. Bopp acknowledges partial support from the INTAS grant 97-31696.

References

- [1] M. Jacob, Phys. Rep. **315**, 7 (1999).
- [2] U. Idschok and et al. [Bonn-Hamburg-Munich Collaboration], “A Study Of Charge Distributions In Inelastic Proton-Proton Collisions,” Nucl. Phys. **B67**, 93 (1973).
- [3] J. Ranft, “Correlations In Multiparticle Production,” Fortsch. Phys. **23**, 467 (1975).
- [4] T. T. Chou and C. N. Yang, Phys. Rev. **D7**, 1425 (1973).
- [5] M. Asakawa, U. Heinz and B. Muller, “Fluctuation probes of quark deconfinement”, hep-ph/0003169.
- [6] S. Jeon and V. Koch, “Charged particle ratio fluctuation as a signal for QGP”, hep-ph/0003168.

- [7] S. Jeon and V. Koch, "Fluctuations of particle ratios and the abundance of hadronic resonances," Phys. Rev. Lett. **83**, 5435 (1999)[nucl-th/9906074].
- [8] F. W. Bopp, "About Measuring Charges In Hard Jets," Nucl. Phys. **B191**, 75 (1981).
- [9] K. Fialkowski and R. Wit, "Are charge fluctuations a good signal for QGP?," hep-ph/0006023.
- [10] C. Quigg and G. H. Thomas, "Charge Transfer In A Multiperipheral Picture," Phys. Rev. **D7**, 2757 (1973).
- [11] C. Quigg, "Local Quantum Number Compensation In Multiple Production," Phys. Rev. **D12**, 834 (1975).
- [12] R. Baier and F. W. Bopp, "Charge Transfer Distribution In Neutral Cluster Models," Nucl. Phys. **B79**, 344(1974).
- [13] P. Aurenche and F. W. Bopp, "Charge And Baryon Transfers In The Dual Unitary Model," Nucl. Phys. **B119**, 157 (1977).
- [14] F. W. Bopp, "The Cluster Model," Riv. Nuovo Cim. **1**, 1 (1978).
- [15] J. Ranft, Phys. Rev. **D 510** 64 (1995); J. Ranft: "DPMJET version II.5", Siegen preprint SI-99-5 (hep-ph/9911213) and SI-99-6 (hep-ph/9911232).